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EFFECTS OF VELOCITY AND MATERIAL PROPERTIES ON DESIGN LIMITS FOR LINEAR SHAPED CHARGES

by

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ABSTRACT. This report discusses the design limits for linear shaped charges that are caused by the behavior properties of the liner material and by the nature of the collapse geometry of the linear shaped charge. In the study the jetting process for both mild steel and copper is examined.

U.S. NAVAL ORDNANCE TEST STATION

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FOREWORD

The study described in this report was conducted at the U.S. Naval Ordnance Test Station as part of the continuing warhead research program that is directed toward improving various types of conventional warheads and accomplishing advanced studies and analyses for anticipated development programs.

The work was accomplished in May 1965 under Bureau of Naval Weapons Task Assignment RMMO-42/994/216-1/F008-08-06.

This report is released at the working level. Because of the continuing nature of the warhead research and development program, refinements and modifications may later be made in this study.

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INTRODUCTION

The U.S. Naval Ordnance Test Station (NOTS) has a continuing interest in linear shaped charges for warhead applications. A preliminary analysis of the collapse process and a discussion of the applications of the end-initiated linear shaped charge are given in Ref. 1. As part of the continuing study, some of the design limits for linear shaped charges have been investigated theoretically. As stated in Ref. 1, the limits to be experienced in the design of a linear shaped charge are caused by the behavior properties of the liner material and also by the nature of the collapse geometry. In this paper, these limits are analyzed for steady-state and non-steady-state conditions.

STEADY-STATE JETTING ANALYSIS

Design limits are set by the velocity of the flow of material into the collapse point. If the collapse angle is too small and the initial wall velocity too high, the material flows into the collapse point at a velocity in excess of the velocity of sound in the material. Instead of a laminar flow, which leads to the jet and slug predicted in the hydrodynamic theory, a shock is formed, and the material merely refracts through the shock instead of turning, as in the laminar flow case, to produce the jet. Hence, a jetless ("no-jet, too-fast") configuration is produced.

On the other hand, if the collapse angle is too large and if the material flows into the collapse point at a velocity that is too slow to produce high enough pressures to cause plastic deformation of the liner material, another jetless ("no-jet, too-slow") configuration results.

If the notation established in Ref. 1 is used for the linear shaped charge, with the angle of 2β separating the two vanes, or walls, and with the initial wall velocity of V_0 (Fig. 1), these limits can be investigated for two materials that are in current use in linear shaped charges. One is mild steel; the other, copper.

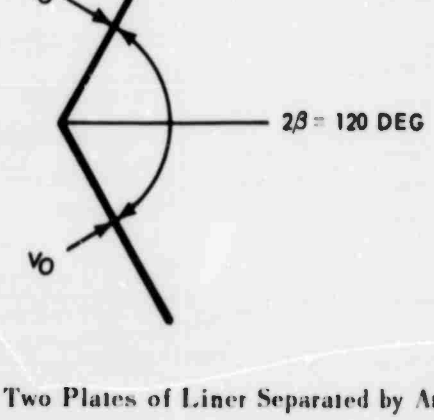

FIG. 1. Two Plates of Liner Separated by Angle 2β.

With a wall velocity of V_o and a collapse angle of β, the flow velocity into the collapse point is

$$V_f = V_o \cot \beta \tag{1}$$

The limit will be reached when the flow velocity is equal to C, the velocity of sound in the medium. If the known values of C for copper and mild steel are used, the limiting angle for the no-jet, too-fast region can be determined by solving the equation

$$\tan \beta = V_o/C \tag{2}$$

There is a slight error introduced by treating C as a constant because, since the material is compressible, the actual shock-wave velocity in the material is a function of the applied pressure. However, for most of the velocity range of interest, the variation in velocity of sound thus introduced is negligible compared with the accuracy of the plotting system (i.e., if C is changed to take in compressibility, the variation on a plot is less than the width of the plotted lines).

The other limit to be considered is the no-jet, too-slow region for the steady-state collapse process. In this problem, the pressure is not determined by the full flow velocity but rather by that portion of the flow velocity that is met by the projected flow velocity from the opposite wall. This is the projection velocity, V_p. At the collision point, because of the action of the wall from both sides, the incident velocity, V_i, for the calculation of pressure would be $2V_p$.

Setting

$$1/2\rho V_i^2 = \sigma_y \tag{3}$$

where

ρ is density, and

σ_y is dynamic yield strength

enables the calculation of the velocity limits for reaching the steady-state dynamic yield point.

Since

$$\sigma_y = 1/2\rho V_i^2 \tag{3}$$

and

$$V_i = 2V_p \tag{4}$$

therefore,

$$\sigma_y = 2\rho V_p^2 \tag{5}$$

But

$$V_p = V_o \cos \beta \tag{6}$$

therefore,

$$\sigma_y = 2\rho V_o^2 \cos^2\beta \tag{7}$$

By using the values for the dynamic yield strength of mild steel and copper, the limit can be determined for the no-jet, too-slow configurations. However, when the pressure applied is just slightly greater than the dynamic yield strength, the materials do not behave as excellent hydrodynamic fluids, but behave instead as a material that is somewhere between a solid and a fluid. Hence, we have a questionable zone of nonhydrodynamic behavior.

From studies of penetration of rods into semi-infinite targets, it has been found that the beginning of the penetration process occurs when the dynamic yield strength of the target is reached. When the pressures occurring at the impact reach a value of 10 times the dynamic yield strength, the behavior is essentially hydrodynamic.

By using this as the basis for an approximation of the limits of the nonhydrodynamic zone, we can again solve Eq. 7, with $10\sigma_y$ substituted for σ_y

$$10\sigma_y = 2\rho V_o^2 \cos^2\beta \tag{8}$$

resulting in a series of zones that can be portrayed as shown in Fig. 2 (for mild steel) and Fig. 3 (for copper). These are a no-jet, too-fast zone, then a central region where the hydrodynamic theory applies, then a questionable zone of nonhydrodynamic behavior, and then a no-jet, too-slow limit zone.

The values used in these calculations are shown in Table 1.

TABLE 1. VALUES USED IN THE CALCULATIONS

Item	Mild steel	Copper
Velocity of sound ($\underline{C}$), ft/sec	19,500	14,900
Density, slugs/ft^3	15.6	17.25
Dynamic yield strength, kilobars	12	26

There is considerable difference between mild steel and copper in behavior in the questionable nonhydrodynamic zone. As soon as the nonhydrodynamic zone border is reached on the side of descending velocities (in other words, moving from the zone where the hydrodynamic theory applies into the nonhydrodynamic zone), the jetting process for steel stops almost immediately, but for copper it continues nearly over to the limit of the no-jet, too-slow zone. Part of this is caused by the anomalous behavior of copper, in which it is very difficult to establish a set value of dynamic yield strength because the dynamic yield strength is very dependent upon the rate of loading.

NON-STEADY-STATE JETTING ANALYSIS

It is possible to produce non-steady-state jets even in the no-jet, too-slow region of the steady-state analysis. This is caused by the jump in pressure that results when the two vanes first contact, before the pressure has been spread throughout the impacting walls. When the shock conditions prevail, the pressure is represented not by $1/2\rho V_i^2$ but in terms of the shock pressure

$$\sigma = \rho C V_i \tag{9}$$

The shock conditions yield much higher pressures than do the steady-state conditions until V_i approaches the value of the velocity of sound in the material. Hence, for copper, it is found that the non-steady-state pressures sufficient for jetting can be produced at essentially a zero-degree collapse angle with velocities as low as 210 ft/sec; whereas for the steady-state jet, the limit at a zero-degree angle for achieving the pressure limit is a velocity of 1,285 ft/sec. For mild steel, the steady-state pressure condition, exceeding the dynamic yield strength, is achieved with a velocity of 896 ft/sec at zero-degree angle; whereas for the unsteady, or shock condition, it is achieved at essentially 100 ft/sec.

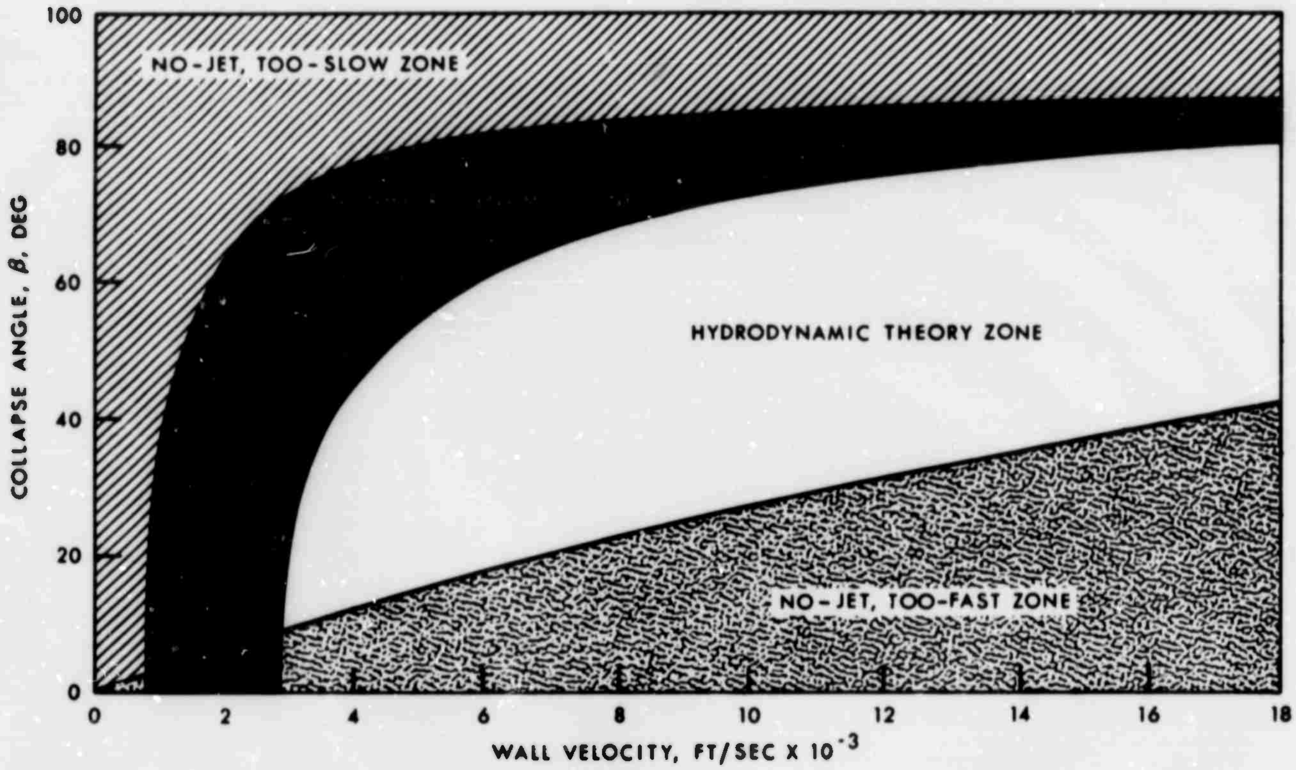

FIG. 2. Linear-Shaped-Charge Limits for Mild Steel.

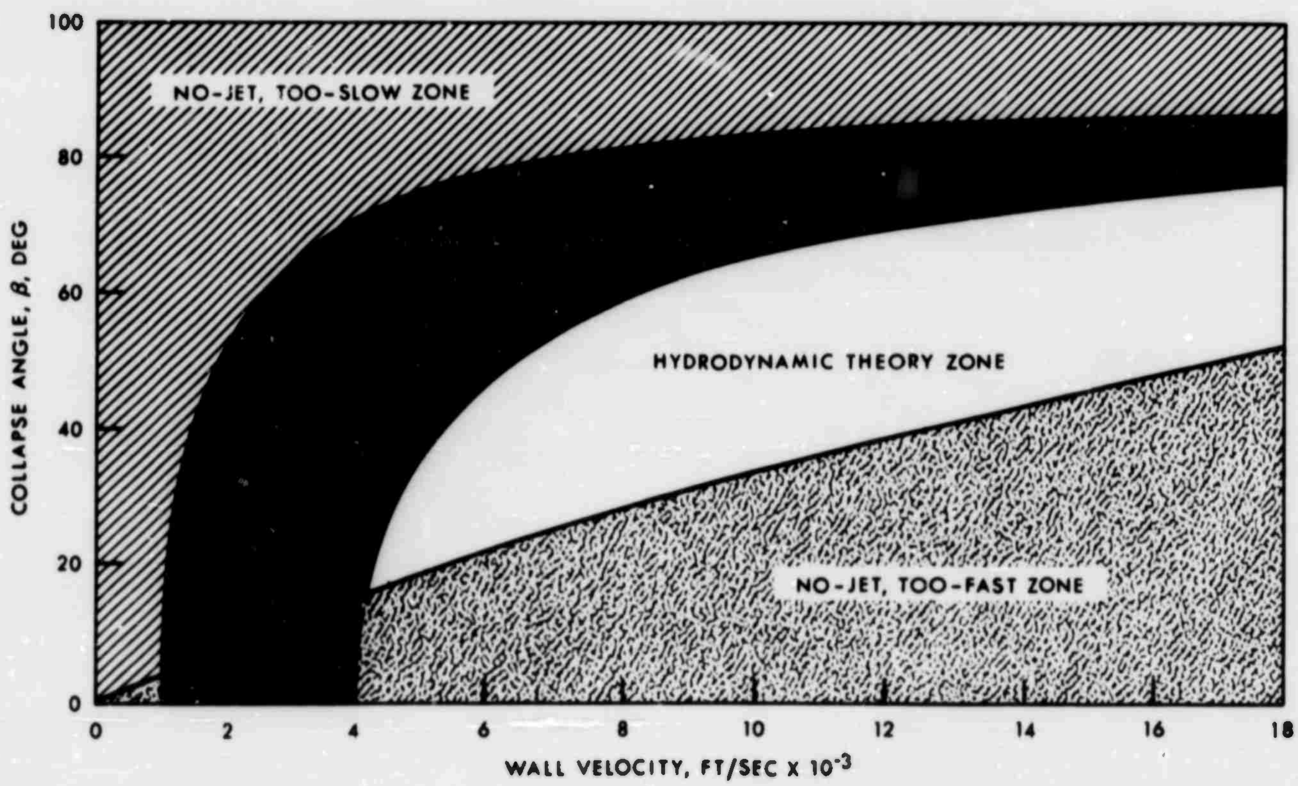

FIG. 3. Linear-Shaped-Charge Limits for Copper.

APPLICATION TO EXPLOSIVE WELDING PHENOMENA

It is possible that the difference in values of the limit conditions for steady-state and non-steady-state jetting may be one of the contributing causes for the appearance of the periodic, or wavy, welds in material in explosive welding studies (Ref. 2 and 3). In such studies, when the material was first brought together, the dynamic yield strength would be exceeded and jetting would begin. As soon as the jetting process had started, it would yield a pressure relief that would decrease the pressure below the limit required for jetting, and the jetting process would stop. Then, since the jetting process had stopped, the material would be as new material striking again and would go back to the shock position, reapplying the pressure that would then cause jetting, which would relieve the pressure. This would occur periodically, giving rise to the wavy welds in material in the explosive welding studies (Fig. 4).

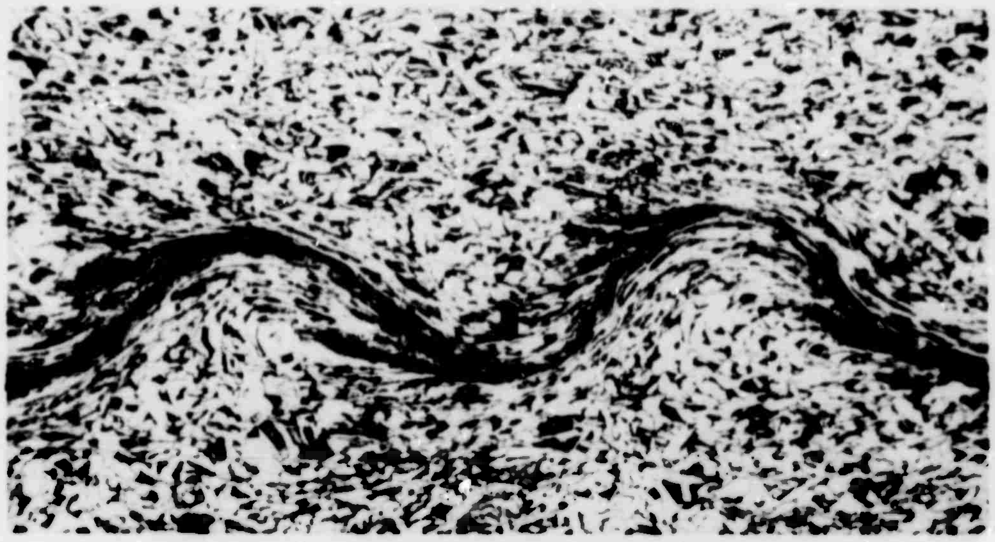

FIG. 4. Microstructure of Wavy Weld in 1018 Steel.

CONCLUSIONS

This short study has shown that there exist (1) various regions in possible designs of linear shaped charges in which no jet results because the flow of material is either too fast or too slow, (2) a questionable zone of nonhydrodynamic behavior, and (3) a zone of design parameters in which the hydrodynamic theory would apply quite nicely.

This information may be used by the designer of the linear shaped charge in determining the type of effect that he will produce. If he desires to produce an all-slug, no-jet charge, he may do it with great confidence of success by designing the charge such that he will be in the no-jet, too-slow region. If he wishes to produce the optimum jet configuration, he will restrict his design to the region where hydrodynamic theory applies and avoid the nonhydrodynamic region.

However, as noted in Ref. 1, because of the gradient in velocity achieved along the vane of a conventional end-initiated linear shaped charge, even though the design parameters are chosen to start at the center of the vane in the hydrodynamic region, as the collapse angle increases and the wall velocity decreases, there is a transition into the nonhydrodynamic zone and very possibly into the no-jet, too-slow region. At this point the distribution of masses between jet and slug predicted by the hydrodynamic theory no longer applies.

REFERENCES

1. U.S. Naval Ordnance Test Station. The Collapse Process and Applications of the End-Initiated Linear Shaped Charge (U), by Robert G. S. Sewell and Paul E. Cordle. China Lake, Calif., NOTS, August 1965. 28 pp. (NAVWEPS Report 8649; NOTS TP 3691), CONFIDENTIAL.

2. Rinehart, John S., and John Pearson. Explosive Working of Metals. London, Pargamon Press, 1963.

3. U.S. Naval Ordnance Test Station. Transactions of the Symposium on Warhead Research, 7-8 May 1963 (U). China Lake, Calif., NOTS, August 1963. Pp. 169-196. (NOTS TP 3301), CONFIDENTIAL.

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